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On the Bulk Compression Characteristics of Wool Fibers

by

P. C. deMaCarty and J. H. Dusenbury

30 June 1955

ON THE BULK COMPRESSION CHARACTERISTICS OF WOOL FIBERS

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P. C. deMacarty* and J. E. Dusenbury**

Abstract

A method has been found to prepare bulk samples of wool fibers in such a way that reproducible compression tests may be performed upon them. An evaluation of the bulk compression characteristics of 29 widely different wool samples shows that compressive load, rather than resilience, serves to bring out differences among them. This finding suggests that quality differences among wools, as determined by handling, is related to differences in the wools' resistance to compression rather than to differences in compressional resilience.

For these 29 wool samples there is an inverse relationship between compressive load and mean fiber diameter. Although this finding is in agreement with similar results reported for cotton fibers, it conflicts with the predictions from a theoretical model that has been proposed to explain the compressional behavior of wool. The theoretical model, which was based on a consideration of bending forces only during compression, has been claimed to fit results found for 310 samples of Merino wool. There is, therefore, an implication either that there is a different dependency of resistance to compression on fiber diameter within

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a wool breed as compared to that among different breeds or that the proposed theory is inadequate.

When the compressing piston size is varied at a constant sample size, for a Targhee 60's wool card sliver, it is found that the effective volume of fibers being compressed is greater than the volume of fibers beneath the piston, probably because of fiber-to-fiber entanglements. The experimental results indicate that a constant area should be added to the compressing piston areas in order to achieve a constant compressive stress. This area increment is independent of sample diameter, providing the sample diameter is sufficiently greater than that of the compressing piston, and this area increment decreases with increasing degree of compression.

Introduction

An important characteristic of a mass of fibers is its behavior during compression. With wool in particular, the "handle" of a sample of bulk fibers is often given special consideration when the quality of the wool is estimated. Such an assessment of quality often involves an operation of squeezing by hand; that is, a subjective kind of bulk compression test. It is the three-fold purpose of this paper to describe a quantitative method for measuring the bulk compression of wool fibers, to discuss the effect of varying experimental conditions on the test results, and to estimate the importance of the different parameters that may be derived from such measurements.

The compression characteristics of fibers in bulk have been described by several authors [4,10,11,15,17], and the subject has been reviewed briefly by Kaswell[8]. In addition, other writers have discussed the compressional and resilience characteristics of yarns and fabrics [1,5,12,13], but this work will not be considered here.

Resilience is a property that has been often discussed and sometimes measured in connection with studies on fibers in all forms from single fibers to finished fabrics. Many definitions have been proposed in the literature, but the one mentioned most frequently has been that described by Dillon in 1947 [3]:

$$\text{Resilience} = \frac{\text{Energy of Retraction}}{\text{Energy of Deformation}} \quad (1)$$

In this instance, resilience is the ratio of the energy recoverable when a deforming force is removed from a test specimen to the energy initially absorbed by the specimen during deformation. It is to be noted that this definition does not attempt to take into account whether the deformation is tensional, compressional, shearing, bending, or a complex combination of various types of strain.

In his now classic 1944 Marburg Lecture, Smith [14] discussed resilience and attempted to relate it to the "hand" of fabrics, and later, in 1946, Mark [9] discussed the relationship of resilience to certain functional characteristics of fabrics in a generalized and qualitative fashion. In 1948, Hamburger [6] proposed the use of another parameter, the elastic performance coefficient, which relates the properties of a "conditioned" sample (previous loading to remove secondary creep) to those of the same sample prior to loading. He pointed out that it is possible for two materials to exhibit the same elastic performance coefficient in tension and yet differ in another important property, the extensibility. He proposed that differences in this property should be evaluated by yet another parameter, the extensibility coefficient.

No attempt will be made here to define additional parameters related to resilience. Instead, it will be shown that resilience, defined according to Equation (1), is not a parameter suitable for characterizing the bulk compression characteristics of wool fibers and that the load measured at certain fixed compressions of an initially "strain-free" sample provides a better measure of differences among wool samples.

Experimental Procedure

All sample preparations and testing operations were carried out at the standard conditions of 70°F and 65% R.H. The compression experiments were carried out with an Instron Tensile Tester [7] equipped with apparatus designed and constructed in this laboratory. This apparatus consists of a compressing piston with an attached weight that is suspended by appropriate linkages from an Instron Load Cell "C". During a compression test, the cross-head is lifted to compress a test specimen, and the compressive load is measured by the amount of "unloading" that occurs during the test of the assembly suspended from the load cell. Special provision is made to prevent jamming and possible rupture of the strain gage because of uncontrolled upward motion of the cross-head. The sample being tested is placed on a plate mounted on the cross-head.

In Figure 1(a) may be seen a 5.50 in. diameter sample situated beneath a 3.00 in. diameter piston prior to compression from an initial gage length of 2.00 in.; in Figure 1(b), the same sample is shown at a compression corresponding to 90% of gage length. Using the Instron extension cycling controls, the sample was compressed to a predetermined extent and immediately retracted at the same rate.

In one set of experiments, those to be considered in the greater detail here, the samples were prepared from card sliver made from the 1952 clip of 60/62's wool from mature Targhee ewes. This wool is one of nine lots grown at the U. S. Sheep Experiment Station in Dubois, Idaho, and their processing characteristics are being extensively studied at Textile Research Institute.

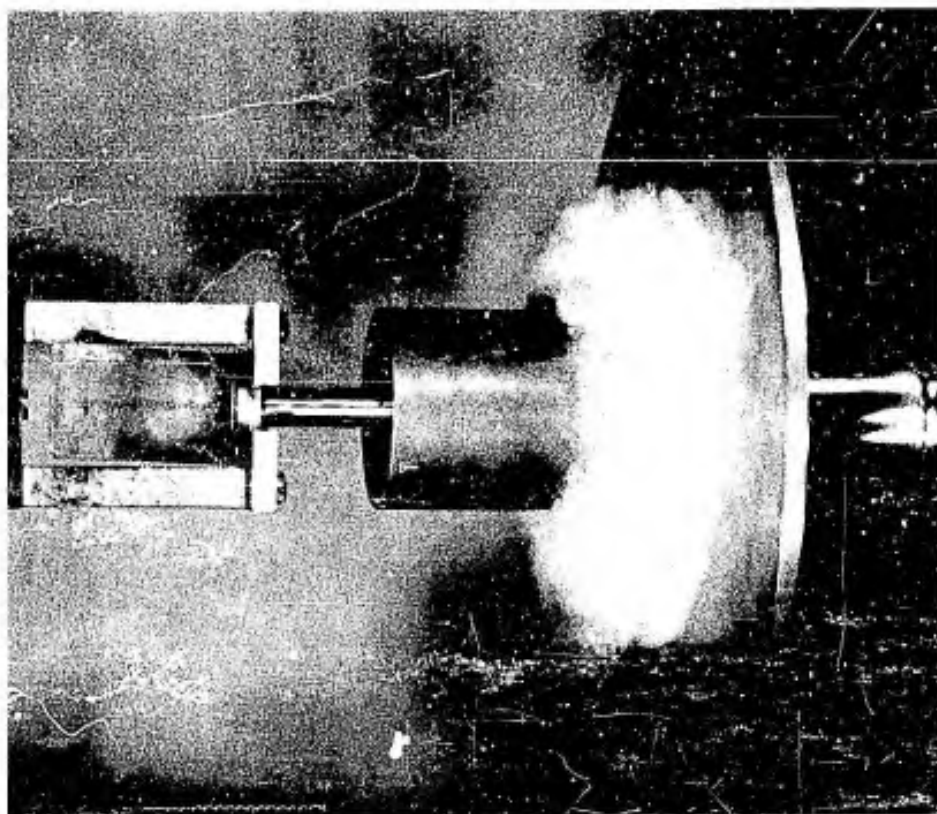
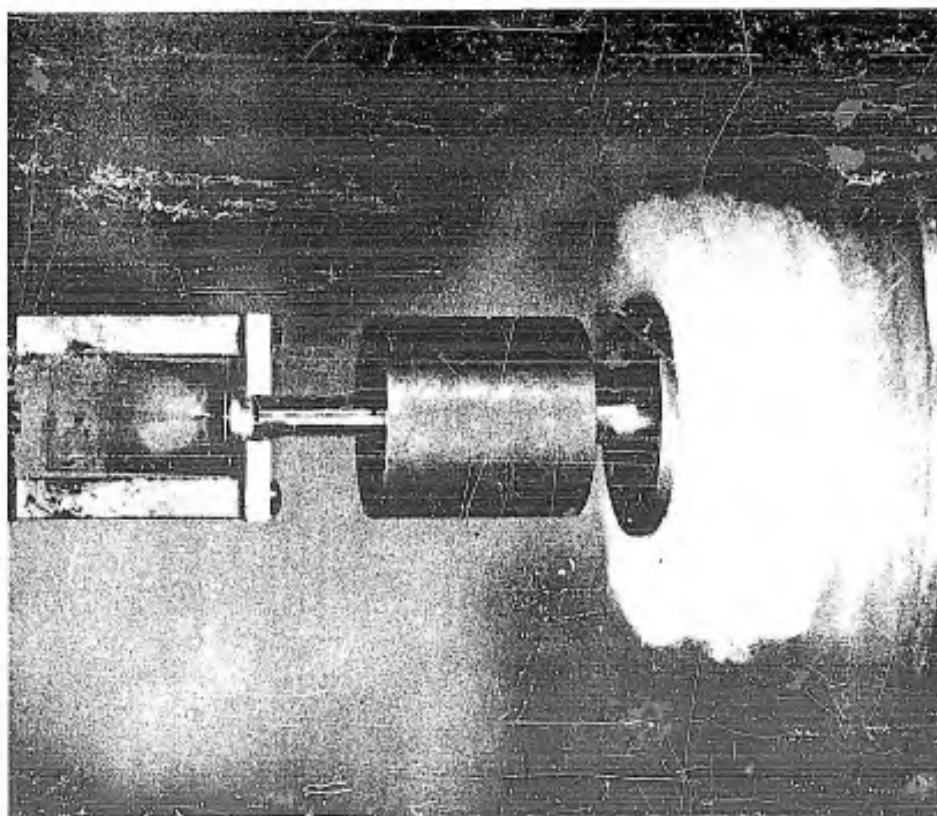


Fig. 1. Compression test on 5.50-in. diameter sample with 3.00-in. diameter piston (a) prior to compression, and (b) at 90% compression.

This wool was selected because of its intermediate character of fineness as an apparel wool and because its physical properties had already been determined. These properties, including a staple-length distribution histogram, are shown in Figure 2 [16]. The single-fiber properties listed in Figure 2 were measured on fibers removed from top rather than card sliver, but they provide a good representation of the properties of fibers from the card sliver.

As received, the Targhee 60's card sliver had a uniform distribution of fibers, and these were rearranged into cylindrical assemblies of known weights and dimensions. The rearrangement was done in a way to insure sample homogeneity; that is, it insured that the distribution of fibers was uniform throughout the sample and that there was no preferential orientation of single fibers with respect to any of the dimensions of the cylindrical sample. The importance of uniform and reproducible preparation of samples can hardly be overemphasized in bulk compression experiments.

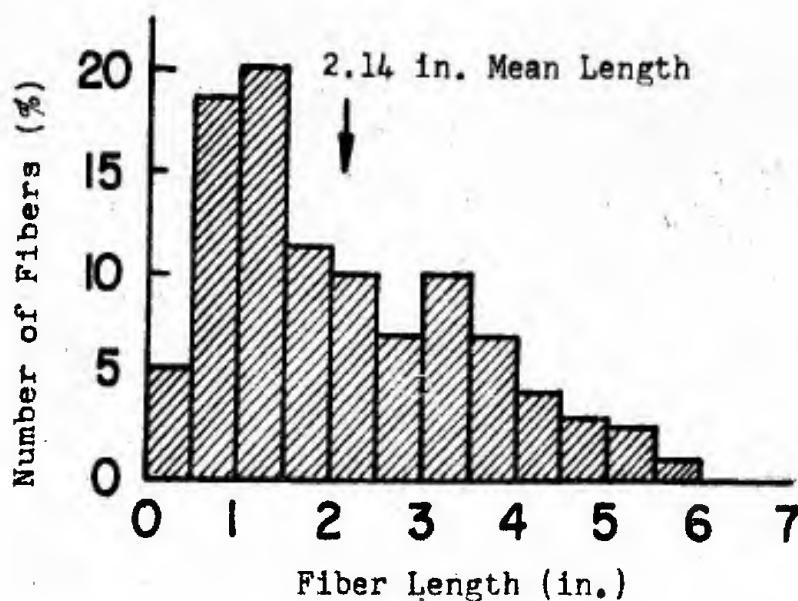
The method used to prepare test specimens is shown in Figure 3. Strips of card wire of the type used on a fancy roll were glued to a board and marked with circles of diameters corresponding to those of the desired test specimens. Fibers were gently embedded in these wires (Figure 3) in such a way as to prevent breaking or excessive stretching. This was done by tamping down small amounts of fibers from a predetermined weight of wool into the area within a proscribed circumference, until an even bulk density of material was obtained throughout. Cylindrical samples, 2 in. in height, were prepared in this way, each sample

Fig. 2. Physical properties of Targhee 60's wool card sliver.

Staple Length (200 fibers)

Mean length = 2.14 in.; standard deviation = 1.46 in.

Staple Length Distribution



Single-Fiber Properties (50 fibers)

Property	Mean Value	Coefficient of Variation (%)
Diameter	27.5 μ	15
Uncrimping stress	0.084 $\times 10^6$ gm.cm. ⁻²	16
Stress at 5% ext.	0.81 $\times 10^6$ gm.cm. ⁻²	10
Stress at 20% ext.	1.00 $\times 10^6$ gm.cm. ⁻²	7
Stress at break	1.28 $\times 10^6$ gm.cm. ⁻²	19
Elastic modulus	26.0 $\times 10^6$ gm.cm. ⁻² for 100% ext.	17
Extension at break	33.8%	29



Fig. 3. Method used in preparing test specimens.

consisting of four layers about 1/2 in. thick. The reproducibility of results from sample to sample indicated that uniformity among different samples was good and that no special effects were produced as a result of compressing layered samples. After preparation each sample was allowed to "relax" for at least one day prior to subsequent testing. In those cases where a sample was tested with one size compressing piston and later tested with a piston of different size, the sample was reprepared lightly and allowed to "relax" between tests.

Three sample sizes were used with their corresponding weights determined so as to preserve the same 2.00 in. depth for each size (Table I); that is, the sample depth and the weight of fiber per unit volume of test sample were kept constant, regardless of the sample diameter. The circular compressing pistons used varied in one-half inch intervals of diameter from 1/2 through 3 in. The gage distance between the plate mounted on the cross-head and the compressing piston was 2.00 in. and, in the case of the experiments carried out on the Targhee 60's wool card sliver, the compressing distance was 1.80 in. or 90% of the sample thickness. At this setting, the first detectable load or resistance to compression by the sample could be measured by the Instron Load Cell. Compression-decompression cycles were run at a constant cross-head speed of 2.00 in./min., corresponding to a compression rate of 100% of gage length/min.

In Figure 4 are shown two typical load vs. compression curves obtained by compressing a 5.50 in. diameter sample with a 3.00 in. diameter piston. The compression of 1.80 in. corresponds to the distance AD (1st cycle) or A'D' (7th cycle) of Figure 4.

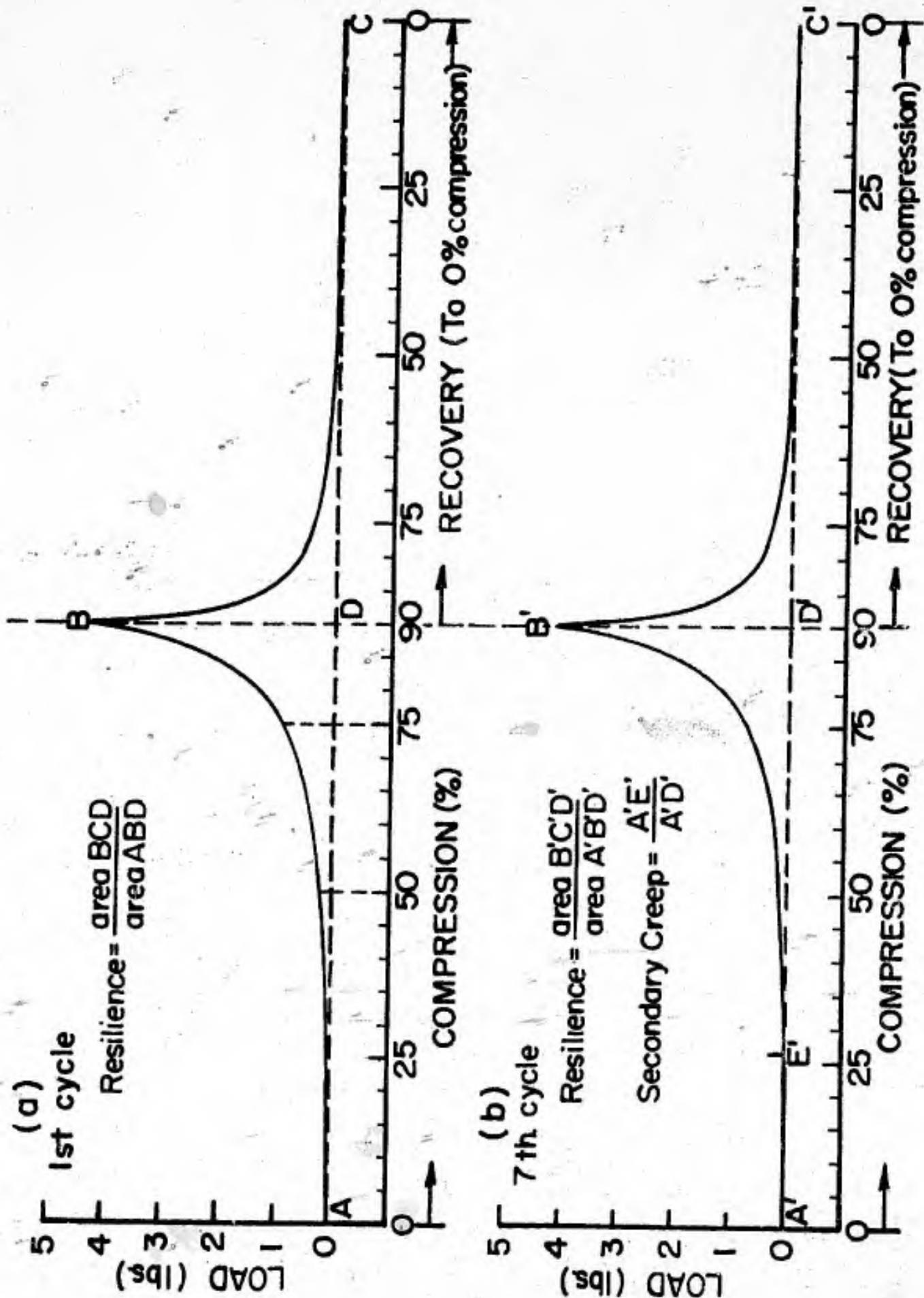


Fig. 4. Load vs. compression plots when 5.50-in. diameter sample is compressed with 3.00-in. diameter piston.

The direction of travel of the cross-head was reversed automatically at points D and D', where the compressive loads had reached the values of B and B', respectively. The Instron tester may be set to perform compression-recovery cycles in succession. Using such an arrangement, after recording the curve of the first cycle, five more cycles were run with recording only of the corresponding maximum loads at 90% compression. Two minutes were allowed to elapse after cycle 6. Compression-recovery cycles 7 and 8 were then run, allowing a two-minute wait between them. It was found that values observed for loads at 90% compression and secondary creep had reached constant values at cycles 7 and 8. Probably the effects of creep, stress relaxation, and the two-minute interval between cycles all interacted to produce steady-state values for the loads at 90% compression and the extent of secondary creep. The following three types of parameters were evaluated as indicated from the curves in Figure 4: loads at various compressions during the compression portion of the test, secondary creep, and resilience. Since the values for the compressive loads were nearly the same for cycles 7 and 8, the mean values from these two cycles were used for the analysis discussed later in this paper.

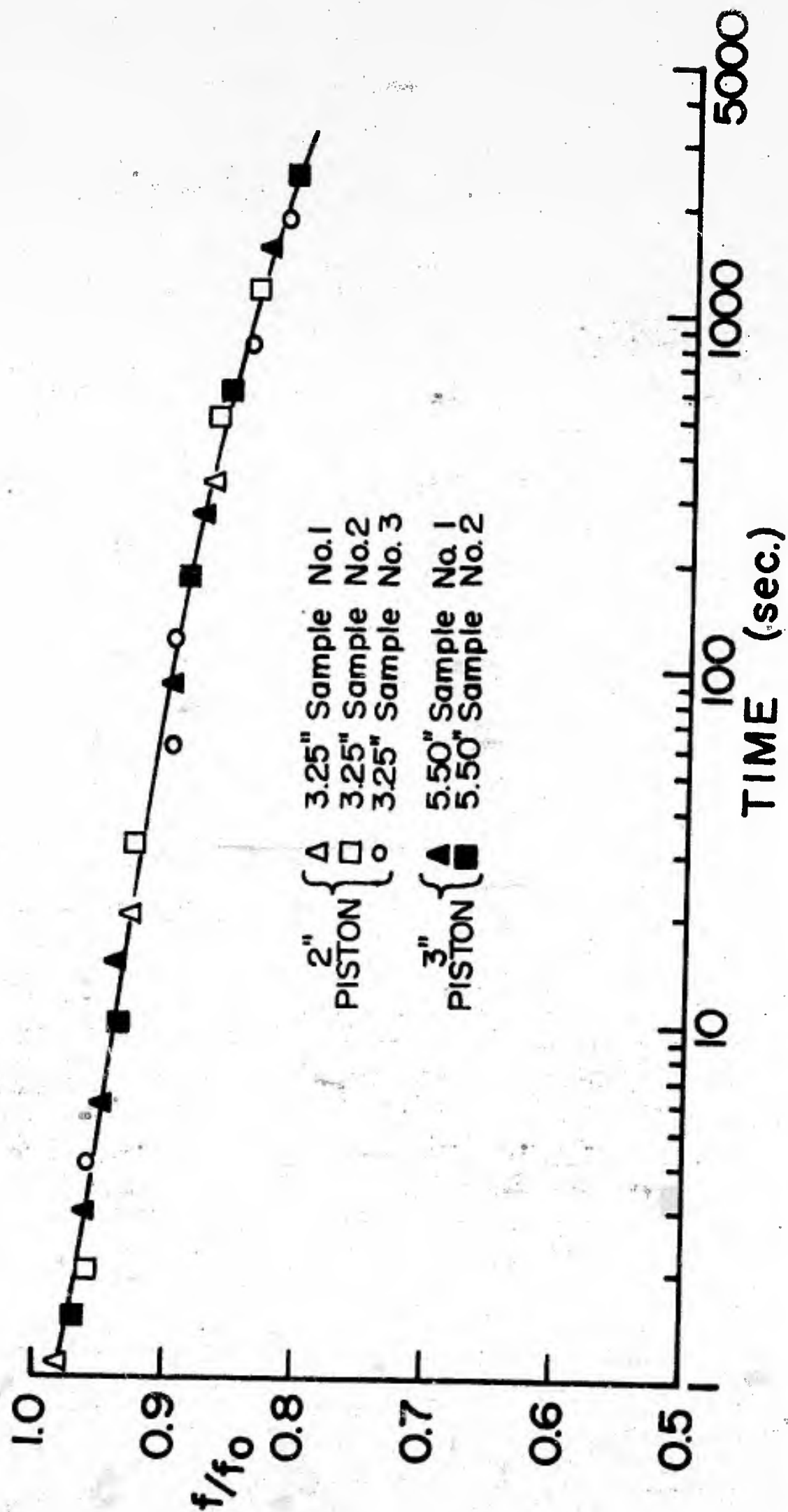
As another check on the reproducibility of the experiments, several load-relaxation experiments were carried out. Because of the response characteristics of the recorder pen at the moment of stopping the cross-head and starting to measure load relaxation, the samples were compressed at 10% of gage length/min. rather than the 100%/min. rate used in other experiments. The data were

then plotted as f/f_0 vs. the logarithm of time, where f is the load measured at any time after stopping the cross-head at 90% compression and f_0 is the load when the cross-head is stopped and load relaxation starts to be measured.

It was found that smooth curves drawn through such data for different samples were superimposable as demonstrated in Figure 5, where points taken from the data of five separate experiments are shown to fit on the same curve. It will be noted that three of the experiments involve a 2.00 in. diameter piston with 3.25 in. diameter samples and two are concerned with a 3.00 in. diameter piston compressing 5.50 in. diameter samples. The experimental conditions are different enough from those reported by Finch [4] so that no direct comparison may be made with his data for wool. He reported, however, an "essentially linear" relationship between f/f_0 and log time up to 1000 seconds, whereas this situation holds only approximately in our experiments. After about 300 seconds, all of the curves derived from the original data show a distinct tendency to become concave downwards.

In another set of experiments, performed in this laboratory by Demiruren in connection with his doctoral thesis at the University of Wyoming [2], the experimental technique previously described was used to determine the compressional characteristics of 29 samples of wool of widely varying staple lengths and fiber diameters. Demiruren used one set of conditions for all his experiments: a 1.50 in. diameter piston compressing 3.25 in. diameter samples, weighing 2.00 gm. each, to 75% compression at the constant rate of 100% of gage length/min. From his measurements he evaluated the

Fig. 5. Load relaxations of several samples at 90% compression.



three parameters: load at 75% compression, secondary creep, and resilience.

Discussion of Results

Using the loads developed at 90% compression as a criterion, comparison was made of the results when 3.25 in. diameter samples were compressed without confining walls (Figure 1) and within a cylindrical confining wall. Under the test conditions used (1.00, 2.00, and 3.00 in. diameter pistons), there was no difference between the walled and wall-less experiments. This indicates that, at least in these experiments, frictional effects caused by the proximity of the outer edge of a compressing piston to the inner surface of a confining wall are unimportant.

In making measurements on samples of a Bengals cotton, Rees found in 1948 [11] that the presence or absence of confining walls had a slight effect on values observed for compressional resilience. In his work the compressing piston was in contact with the inner walls of the confining cylinder, whereas in this work an appreciable distance existed between them. The experiments reported here show the experimental variance of compressional resilience values to be rather high and would indicate that the differences in resilience observed by Rees may not be statistically significant. As a result of his walled vs. wall-less comparisons, Rees adopted as a standard method tests carried out without confining walls, the method used in the experiments with which this paper is concerned.

The results of the previously described measurements by Demiruren [2] are most interesting. Over the wide range of wools

tested, the resilience values obtained showed a very weak dependence on mean fiber diameter and mean staple length, whereas the secondary creep and maximum load values (75% compression) appeared to be considerably more sensitive to changes in fiber dimensions. The compressive load appeared to be most sensitive, with loads observed for a 70's wool (fine grade) being about ten times greater than those observed for a 36's wool (extremely coarse grade). Correlation coefficients illustrating these observations are shown in Table II. These results indicate that subjective differences between wool fiber types, as determined by hand squeezing, may be due to differences in maximum load values rather than to differences in resilience.

The inverse relationship between the compressive load and the fiber diameter indicates further that the measurements reflect a cooperative property of the entire fiber assembly rather than properties of the individual fibers such as the bending or extensional moduli of elasticity. If one considers the compressive loads to depend only upon bending or extensional moduli of the single fibers and considers the loads to be simple additive functions of the loads on the single fibers, it may be shown that these loads should either vary directly with the square of the fiber diameter, in the case of pure bending, or be independent of fiber diameter, in the case of pure extension. The crimp of the single, constituent fibers may well be important, however, and should be considered in a more detailed analysis than that mentioned briefly above.

A more sophisticated analysis of this kind of problem has been performed by van Wyk [15], who derived a relationship between the pressure (compressive load) and the volume of the mass of

fibers being compressed. He assumed that the compression consisted only of bending the fibers and he treated the mass of fibers as a randomly oriented group of cylindrical rods. Twisting, slippage, and extension of the fibers were ignored, and consideration was given to the number of times one rod would come in contact with another during compression. The equation derived from these considerations is:

$$dp = -\left(\frac{kY}{12v^4} \cdot \frac{m^3}{\rho^3}\right) dv \quad (2)$$

where dp is the differential change of pressure corresponding to the differential change of volume dv , k is a constant of proportionality, Y is Young's modulus through bending, v is the volume of the mass of fibers, and m and ρ are the mass and density, respectively, of the wool fibers. It is to be noted that this equation predicts that compressive loads should be independent of fiber diameter. Integration of Equation (2) leads to a relationship in which the pressure varies with the inverse cube of the volume, a relationship which appeared to be satisfied by data obtained by van Wyk on three different Merino wool samples.

In testing 310 different Merino wool samples, van Wyk found no correlation between resistance to compression and fiber diameter, an apparent confirmation of Equation (2). Unfortunately, such a selection of wool samples would not provide a very wide range of fiber diameter. The much wider range considered by Demiruren and Burns [2] provides a more severe test of van Wyk's theoretical model, and, as already noted, their results show a negative dependence of compressive load on fiber diameter. After

an attempt to eliminate the effect of crimp differences among the 310 Merino wools, van Wyk found a positive partial correlation coefficient between compressive load and fiber diameter and mentioned "that an influence of fibre diameter may be masked by the crimping". Again, it is to be noted that the range of crimp, measured as number of crimps per unit length, among Merino wools may not provide a severe enough test of the theory.

There are two possible explanations for the apparent disagreement between the experiments reported by Demiruren and Burns [2] and those of van Wyk [15]. One is that the dependence of resistance to compression on fiber diameter may be different within a single breed of sheep from what it is among different breeds. Such a difference might be related to a similar one involving crimp levels within a breed as compared to those among breeds. Only further experimentation can tell the answer to this problem.

Another, and perhaps more obvious explanation, is that van Wyk's theoretical model needs revision. For one thing, and van Wyk has acknowledged this as a possible objection, only the total length, that obtained by considering all the fibers laid end-to-end, is used in deriving the pressure-volume equation. Staple length differences have been completely ignored. Variations in "element length", the distance between adjacent points of contact in van Wyk's model, have also been ignored, but, if crimp is an important factor, it should have a significant effect on the "element length".

The only other work related to this discussion is that

mentioned previously of Rees in 1948 [11]. Rees tested five different cotton breeds and found at higher pressures that the finer the cotton the greater is its specific volume. This result means that at the same volumes (the same compressions) the compressive loads varied inversely with fiber diameter, the same type of relationship found for different breeds of wool. It is also interesting that Rees found no significant correlation of compressional resilience with fiber diameter among his five different cottons. As mentioned earlier, it is surprising in view of this that he believed the presence or absence of confining walls during a compression test could have a significant effect on the determination of resilience.

The experiments carried out on bulk samples prepared from Targhee 60's card sliver will now be considered. As mentioned previously, these involved the compression of three different diameter samples with compressing pistons of varying diameter. Some typical values of parameters derived from load vs. compression curves are shown in Table III. It may be seen that the variance of the resilience measurements is far higher than that of the corresponding measurements for compressive load. As discussed earlier, the values observed for maximum load and secondary creep have reached essentially constant values at cycles 7 and 8.

When the compressing piston size was varied at a constant sample size, it was found that the effective volume of fibers being squeezed was greater than the volume of fibers directly beneath the piston. The compressive loads (F_1) developed at a compression (c) were greater than expected to maintain a constant

compressive stress (S_c). That is, the area of the compressing piston (A_i) needed correction by a corresponding area increment (a_i) to maintain constant stress, or

$$F_i = S_c (A_i + a_i) \quad (3)$$

Typical plots showing how the load developed at 90% compression (average of cycles 7 and 8) varied with the area of the compressing piston are given in Figures 6, 7, and 8, where the sample diameter sizes were 3.25 in., 5.50 in., and 9.80 in., respectively. The indicated limits above and below each mean value (open circles) show the experimental range of the observed loads, and the solid circles indicate the mean values for each set of measurements through which the corresponding least-mean-squares lines have been drawn. It may be seen from such plots that a linear relationship exists between maximum load (F_i) and compressing piston area (A_i) and that the straight line drawn through the experimental points intercepts the " F_i axis" at a value greater than zero.

The slopes of such straight lines (dF_i/dA_i) are given by differentiation of Equation (3):

$$\frac{dF_i}{dA_i} = S_c \left[1 + \frac{da_i}{dA_i} \right] \quad (4)$$

The results of all the experiments indicated the value of da_i/dA_i to be zero; that is, values calculated for a_i appeared to be constant at a single compression and sample diameter over the range of piston sizes used.

Fig. 6. Maximum load vs. area of compressing piston for 3.25-in. diameter samples at 90% compression (average of cycles 7 and 8).

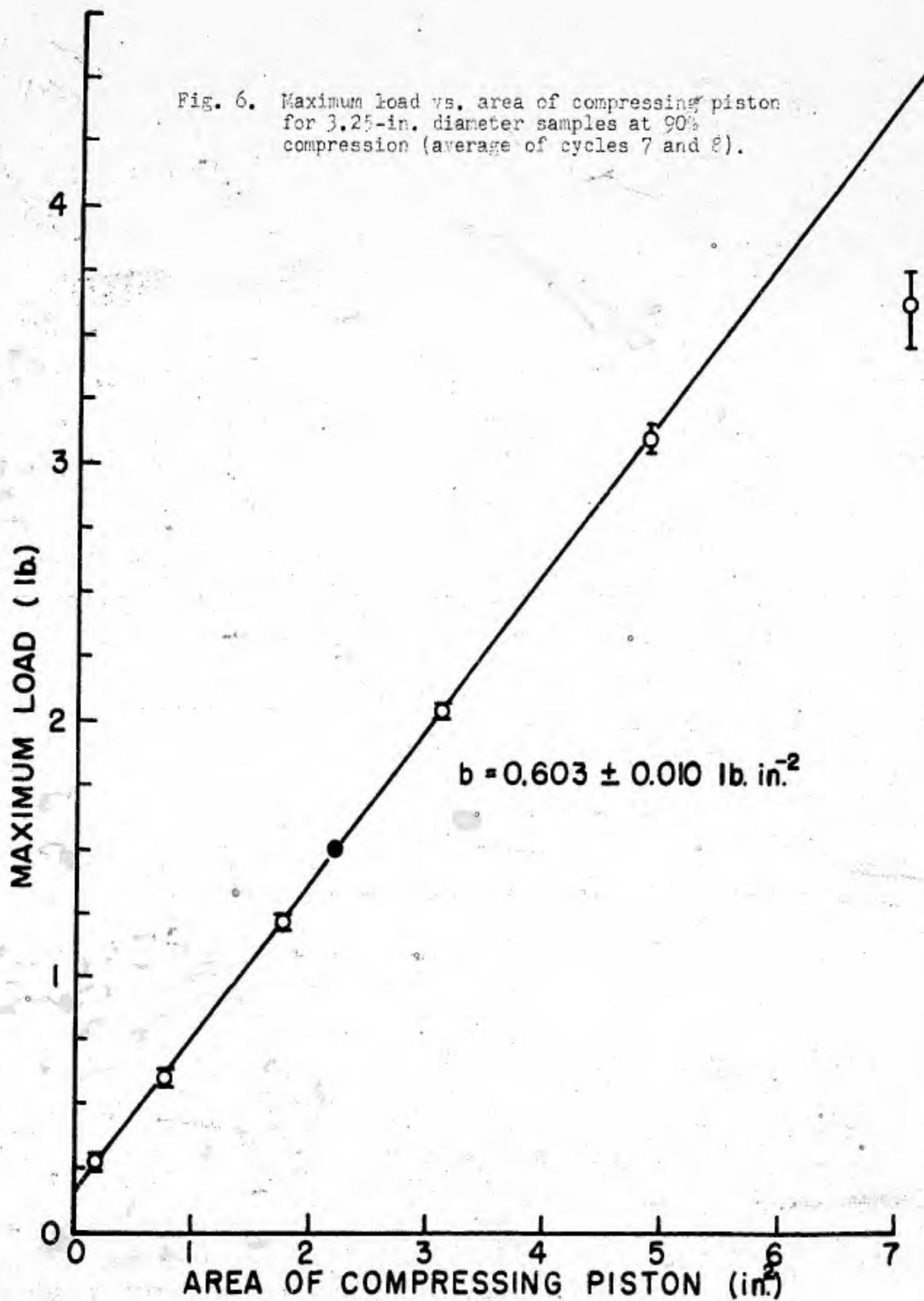


Fig. 7. Maximum load vs. area of compressing piston for 5.50-in. diameter samples at 90% compression (average of cycles 7 and 8).

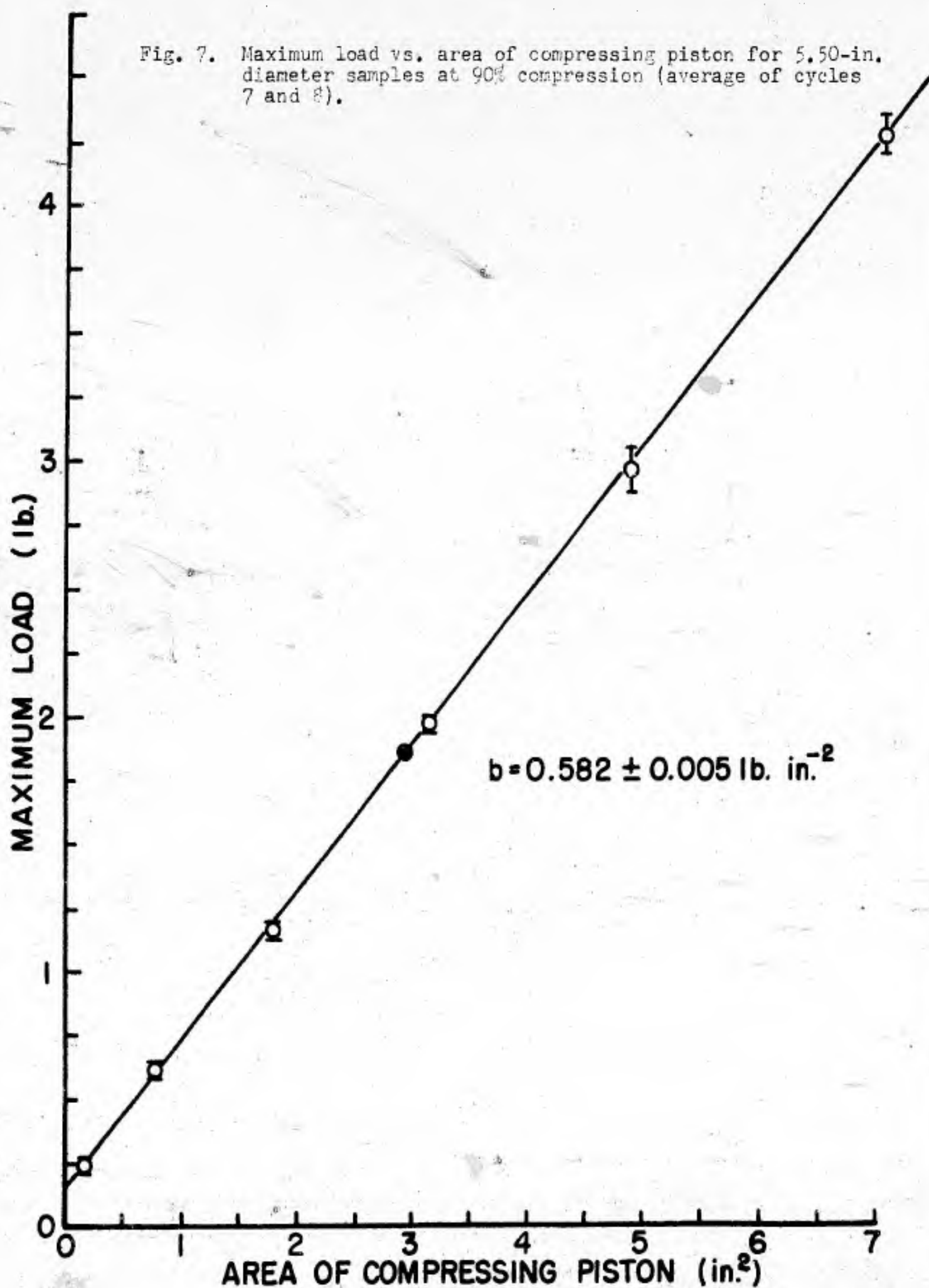


Fig. 7. Maximum load vs. area of compressing piston for 5.50-in. diameter samples at 90% compression (average of cycles 7 and 8).

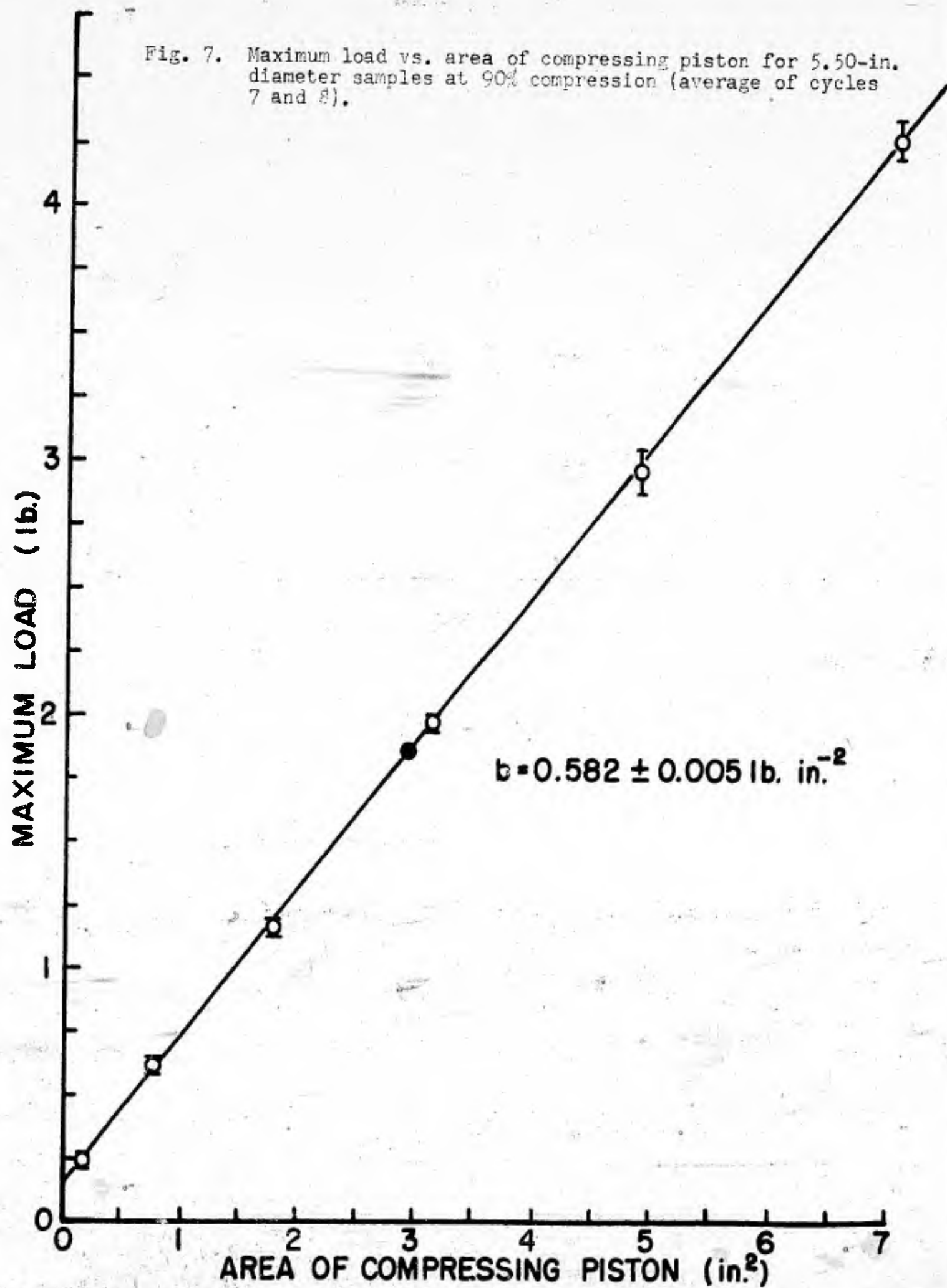
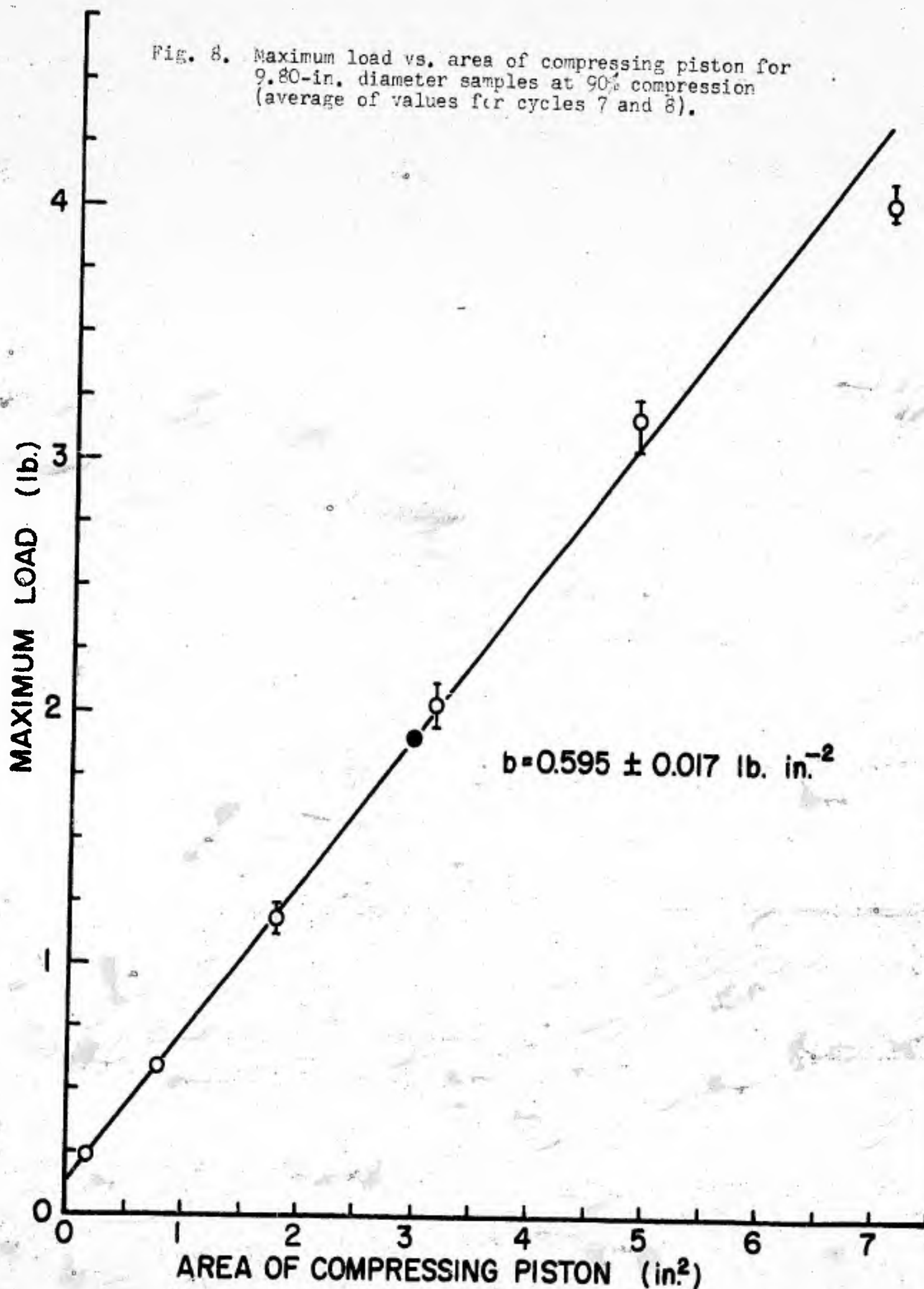


Fig. 8. Maximum load vs. area of compressing piston for 9.80-in. diameter samples at 90% compression (average of values for cycles 7 and 8).



An example of how this was determined is given in the data listed in Table IV. The linear relationship between F_i and A_i shows that da_i/dA_i must be a constant or zero. The values of the least-mean-squares slopes with their corresponding 95% confidence limits (the "b's" in Figures 6, 7, and 8) may be taken as being equal to S_c as a first approximation. Using this S_c value, the corrective area increases (a_i) may be calculated for each of the corresponding maximum load values (F_i) at all the piston sizes (A_i). These calculated a_i values are shown listed for a typical case in Table IV. A plot of the a_i values listed there vs. the radii of the corresponding compressing pistons is given in Figure 9 (open circles). It may be seen from the value given for "b" (the regression coefficient) with its corresponding 95% confidence limits that the slope of the least-mean-squares line does not differ from zero. The solid circle corresponds again to the mean values for a_i and compressing piston radius through which the calculated line has been drawn. Since there is no dependence of a_i upon the size of the compressing piston, it is possible to calculate a mean value of a_i and its 95% confidence level. Such calculated values for \bar{a}_i are shown in Table IV.

A possible criticism of this method of analysis is that the variance of the compressive loads is greater at the larger piston sizes, and this is manifested by there being a greater variance in the calculated area increments at the larger piston sizes (Figure 9). A more rigorous analysis, in the statistical sense, would be obtained by using the logarithms of the F_i and A_i values, but such an approach is complicated by the necessity

of then determining S_c as an intercept and by the presence of the summation term $(A_i + a_i)$ in Equation (3).

The necessity of adding a corrective area to that of the compressing piston is undoubtedly due to fiber entanglements among fibers beneath the piston and fibers beyond the edge of the piston. Since the area increase (a_i) is constant with increasing compressing piston size, the corresponding corrective radius decreases with increasing piston size. Therefore, providing the sample size is large enough, the effect of the corrective area increase tends to vanish as the compressing piston size is increased.

Using the method of data analysis outlined previously, values of compressive stress (S_c) and corresponding area increments (\bar{a}_i) were calculated for the three piston sizes at cycle 1 and at the average of cycles 7 and 8 for the three compressions of 50%, 75%, and 90% (Figure 4). These calculated values are listed in Table V. The area increments at low compressions were large enough to suggest that the compressive loads, in the case of the 3.00 in. diameter piston squeezing the 3.25 in. diameter samples, would be too small to fall on the straight line plot of maximum load (F_i) vs. area of compressing piston (A_i). This was found to be the case, and, accordingly, the F_i values obtained with the 3.00 in. diameter piston were excluded from the analysis of the data for the 3.25 in. diameter samples. When, for comparison, these data were also excluded from the analysis of the data for the 5.50 and 9.80 in. diameter samples, no significant change was observed in the calculated values for S_c and \bar{a}_i (Table VI).

The calculated corrective area increases show a marked

decrease with increasing compression, and this suggests that effects caused by fiber-to-fiber entanglements extending beyond the edge of the compressing piston tend to vanish as the compression approaches 100%. The differences among the three different diameter samples are slight or negligible, save in one instance. The data for the average of cycles 7 and 8 are in general accord with those of cycle 1 except at 50% compression. Here, the effect of secondary creep was to lower appreciably the observed compressive loads. These loads were rather difficult to read from the load vs. compression plots of the Instron tester, and, accordingly, there was more inaccuracy associated with these small values than with any of the other compressive loads. This, rather than any real differences among the three different diameter samples, is probably the cause of the apparent differences to be noted in Tables V and VI.

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TABLE I. Sample Sizes and Weights

Sample Diameter (in.)	Sample Weight (gm.)	Specific Volume (cm. ³ gm. ⁻¹)
3.25	2.00	136
5.50	5.72	136
9.80	18.20	136

TABLE II. Compression Test Correlations

Correlation Coefficients Observed for Mean Values of 29 Different Wool Samples			
Variable "Y"	vs.	Variable "X"	Simple Correlation Coefficient (r)
Maximum Load		Fiber Diameter	-0.702***
Maximum Load		Fiber Length	-0.755***
Resilience		Fiber Diameter	+0.321*
Resilience		Fiber Length	+0.380

* Correlation significant at 5% level ($r=0.367$ or more).
 *** Correlation significant at 0.1% level.

TABLE III. Typical Values of Parameters Obtained from
Load vs. Compression Curves

		5.50 in. Diameter Samples Taken to 90% Compression by:								
Sample No.	Cycle No.	1.00 in. diameter piston			2.00 in. diameter piston			3.00 in. diameter piston		
		Maximum Load(lb)	Secondary Creep (%)	Resilience (%)	Maximum Load(lb)	Secondary Creep (%)	Resilience (%)	Maximum Load(lb)	Secondary Creep (%)	Resilience (%)
1	1	0.640	-	61.7	2.04	-	44.7	4.36	-	50.8
	7	0.618	32.6	65.0	2.00	29.4	62.5	4.20	29.6	61.8
	8	0.614	34.5	58.8	2.00	28.3	54.5	4.20	26.7	59.8
2	1	0.636	-	56.1	2.04	-	57.2	4.49	-	54.2
	7	0.614	29.6	51.3	2.00	34.7	63.5	4.37	29.9	62.8
	8	0.612	38.6	58.4	2.00	35.8	54.6	4.35	27.0	63.4
3	1	0.648	-	45.9	2.03	-	58.5	4.34	-	48.3
	7	0.628	34.1	58.3	1.96	33.0	45.0	4.27	2.79	62.8
	8	0.620	33.7	61.6	1.96	32.4	46.0	4.26	27.8	73.0

TABLE IV. Typical Values Derived from Measurements of Compressive Load

5.50 in. Diameter Samples Taken to 90% Compression					
Piston		Cycle 1		Average of Cycles 7 and 8	
Diameter (in.)	Area- A_i (in. ²)	Max. Load- F_i (lb.)	Corrective Area Increase- a_i (in. ²)	Max. Load- F_i (lb.)	Corrective Area Increase- a_i (in. ²)
0.50	0.196	0.263	0.244	0.248	0.230
		0.270	0.256	0.254	0.241
		0.280	0.272	0.265	0.259
1.00	0.785	0.640	0.286	0.616	0.274
		0.636	0.279	0.613	0.268
		0.648	0.299	0.624	0.287
1.50	1.767	1.190	0.224	1.160	0.226
		1.200	0.240	1.170	0.244
		1.180	0.207	1.140	0.192
2.00	3.142	2.040	0.271	2.000	0.295
		2.040	0.271	2.000	0.295
		2.030	0.254	1.960	0.226
2.50	4.909	3.040	0.176	2.970	0.195
		3.170	0.394	3.065	0.358
		2.970	0.059	2.870	0.023
3.00	7.069	4.360	0.224	4.200	0.149
		4.490	0.442	4.360	0.424
		4.340	0.191	4.265	0.260
Compressive Stresses (lb. in. ⁻²)					
$b \pm t_{0.05} \sigma_b$		0.598 \pm 0.010		0.582 \pm 0.005	
Corrective Area Increases (in. ²)					
$\bar{a}_i \pm t_{0.05} \sigma_{\bar{a}_i}$		0.255 \pm 0.040		0.247 \pm 0.041	

TABLE V. Compressive Stresses and Corresponding Corrective Area Increments Derived from Compression of Bulk Wool Samples

Sample Diameter (in.)	Compressive Stress $^* - S_c$ (lb.in. $^{-2}$)		Area Increment $^* - \bar{a}_i$ (in. 2)	
	Cycle 1	Average of Cycles 7 and 8	Cycle 1	Average of Cycles 7 and 8
		50% Compression		
3.25**	0.0210 \pm 0.0025	0.0109 \pm 0.0013	1.288 \pm 0.192	1.754 \pm 0.194
5.50	0.0216 \pm 0.0020	0.0130 \pm 0.0011	1.284 \pm 0.219	0.983 \pm 0.197
9.80	0.0246 \pm 0.0017	0.0165 \pm 0.0015	1.340 \pm 0.155	0.618 \pm 0.214
		75% Compression		
3.25**	0.1035 \pm 0.0044	0.0856 \pm 0.0042	0.779 \pm 0.068	0.782 \pm 0.080
5.50	0.1064 \pm 0.0036	0.0899 \pm 0.0019	0.707 \pm 0.078	0.630 \pm 0.048
9.80	0.1106 \pm 0.0028	0.0916 \pm 0.0028	0.762 \pm 0.058	0.702 \pm 0.068
		90% Compression		
3.25**	0.621 \pm 0.011	0.603 \pm 0.010	0.247 \pm 0.030	0.237 \pm 0.025
5.50	0.598 \pm 0.010	0.582 \pm 0.005	0.255 \pm 0.040	0.247 \pm 0.041
9.80	0.613 \pm 0.021	0.595 \pm 0.017	0.270 \pm 0.079	0.258 \pm 0.065

* Limits shown are 95% confidence levels of the corresponding mean values.

** Data for 3.00 in. diameter piston excluded from the analysis.

TABLE VI. Compressive Stresses and Corresponding Corrective Area Increments Derived from Compression of Bulk Wool Samples; 3.00 in. Diameter Piston Data Excluded from the Analysis

Sample Diameter (in.)	Compressive Stress* $-S_c$ (lb.in. ⁻²)		Area Increment* $-\bar{a}_i$ (in. ²)	
	Cycle 1	Average of Cycles 7 and 8	Cycle 1	Average of Cycles 7 and 8
50% Compression				
3.25	0.0210±0.0025	0.0109±0.0013	1.288±0.192	1.754±0.194
5.50	0.0229±0.0013	0.0146±0.0013	1.123±0.078	0.703±0.145
9.80	0.0247±0.0022	0.0171±0.0018	1.327±0.148	0.542±0.169
75% Compression				
3.25	0.1035±0.0044	0.0856±0.0042	0.779±0.068	0.782±0.080
5.50	0.1042±0.0048	0.0884±0.0030	0.754±0.046	0.667±0.025
9.80	0.1118±0.0030	0.0943±0.0043	0.735±0.044	0.628±0.074
90% Compression				
3.25	0.621 ±0.011	0.603 ±0.010	0.247±0.030	0.237±0.025
5.50	0.592 ±0.014	0.576 ±0.018	0.202±0.047	0.240±0.048
9.80	0.631 ±0.021	0.619 ±0.021	0.218±0.054	0.182±0.056

* Limits shown are 95% confidence levels of the corresponding mean values.

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